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Case Histories of Damaging Earthquakes

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ABSTRACT

This paper contains illustrative case histories of the principal "forensic lessons" learned from multidisciplinary postearthquake investigations [United States Geological Survey, 1993] of damaging earthquakes throughout the world. Since 1980, the most notable earthquakes include those that struck Kobe, Japan in 1995, Northridge, California in 1994, Hokkaido-Nansei-Oki, Japan and Khalari, India in 1993, Landers, California and Erzincan, Turkey in 1992, Costa Rica in 1991, the Philippines in 1990, Loma Prieta, California in 1989, Spitak, Armenia in 1988, Mexico in 1985, and El Asnam, Algeria and Irpinia, Italy in 1980. Individually and collectively, these earthquakes have served as scientific laboratories to show where things went wrong in the planning, siting, design, construction, and use of various types of buildings and lifeline systems founded on soil or rock both close to and far from the causative fault system. They have shown that communities keep on making nine basic mistakes which cause damage to be exacerbated and failure modes to be repeated in earthquake after earthquake.

KEYWORDS

Postearthquake investigations, source directivity, transfer of stress, ground shaking, soil amplification, soil-structure resonance, liquefaction, landslides, tsunamis, aftershocks.

INTRODUCTION

A number of notable damaging earthquake disasters throughout the world have now been investigated by organized multidisciplinary teams of earth scientists, engineers, health care specialists, architects, planners, and emergency managers (Earthquake Engineering Research Institute, 1991). These earthquakes have served as "scientific laboratories" for scientists, engineers, and others to acquire new perishable and non-perishable data and to test theories, concepts, policies, and practices for siting, designing, and constructing various types of buildings and lifeline systems on soil or rock located close to and far from the causative fault system in low- as well as high-seismicity regimes.

These unplanned "scientific laboratories" include the earthquake disasters that struck Kobe, Japan in 1995, Northridge, California in 1994, Hokkaido-Nansei-Oki, Japan and Khilari, India in 1993), Landers-Big Bear, California, Dashour, Egypt, off the coast of Nicaragua and Erzincan, Turkey in 1992, Costa Rica in 1991, Manjil, Iran and the Philippine Islands in 1990, Loma Prieta, California in 1989, Spitak, Armenia in 1988, Mexico in 1985, and El Asnam, Algeria and Irpinia, Italy in 1980. These and other scientific laboratories have shown what usually happens, why certain damage patterns and damage modes keep recurring, and what is needed to reduce the vulnerability of buildings and lifeline systems in future earthquakes. They have highlighted the following mistakes made repeatedly in every country:

1. Underestimating the strength, duration, and frequency composition of ground shaking.
2. Failing to provide adequate lateral resistance.
3. Lack of consideration of soil amplification and soil/structure resonance.
4. Lack of consideration of the effects of shallow depths of focus, source directivity, or fault rupture.
5. Ignoring the possibility of long-duration acceleration pulses close to the causative fault.
6. Failing to identify soils and slopes susceptible to permanent ground displacement (i.e., liquefaction and/or landslides).
7. Introduction of asymmetry, irregularity, and horizontal and vertical discontinuities in mass, strength, and stiffness in the building configuration during the design phase.
8. Ignoring the possibility of hammering by adjacent structures

during urban planning.
9. Ignoring the possibility of tsunami flood waves at coastal locations.

Sixteen "earthquake laboratories" representing different cultural and tectonic settings are summarized below to illustrate the range and commonality of the lessons that can benefit all nations.

January 17, 1995 Great Hyogo-Ken Nambu, Japan (Kobe) Earthquake [Earthquake Engineering Research Institute, 1995]

This M 6.9 earthquake, which occurred at 5:46 a. m. 20 km from Kobe on a right-lateral-strike-slip fault instead of the expected scenario of a similar or larger magnitude subduction zone earthquake located much farther away in the trench, is representative of the type of urban earthquake disaster that can be expected when a combination of negative geotechnical factors are involved. The negative factors in this case included: 1) a damaging level magnitude, 2) an epicenter close to Kobe, 3) a relatively shallow depth of focus, 4) fault rupture directivity effects focused toward Kobe, 5) enhanced ground shaking due to amplification of soft soils underlying much of Kobe, and 6) liquefaction and lateral spreading of man made soils in the port area. The surprises included: 1) the extent of the damage of the elevated Hanshin expressway, 2) the nature and extent of the damage to the port facilities, 3) the collapse of so many single family dwellings, 4) damage to welded steel frame buildings, and 5) the long duration acceleration pulse in the ground motion. The economic losses are believed to have exceeded $140 billion; deaths, 5,600, and injuries, 26, 000; and a homeless toll of over 250,000. The disaster led to a renewed effort by the Japanese Government to implement improved earthquake loss prevention and mitigation measures and to strengthen earthquake preparedness and emergency response.

January 17, 1994 Northridge, California Earthquake [State of California, 1995]

This M 6.7 earthquake, which occurred at 4:31 a. m., illustrates what can happen in the epicentral area of an urban earthquake generated on a "blind" thrust fault. It is representative of the least frequent but most destructive as a single event of the three types of scenario earthquakes that are being used at present for risk assessments and to increase preparedness and to foster mitigation in the Los Angeles area. In this case, instead of "the big one" caused by rupture of the San Andreas fault or a moderate one caused by rupture of the Newport-Englewood fault, a blind thrust fault ruptured in response to the ongoing north-south compression caused by the big bend in the San Andreas fault system which marks the active boundary of the North American and Pacific plates. The earthquake, which did not rupture the surface, produced several "surprises": 1) verification of the web of "blind thrust faults" beneath Los Angeles, one of which produced the 1971 San Fernando earthquake, 2) the exceptionally strong horizontal and vertical ground accelerations in a 20 x 20 square kilometer epicentral area which approached 2 g, a factor of more than 2 greater than the expected level of ground shaking and the actual design value prescribed in the building code, 3) ground motion characterized by a long duration acceleration pulse (i.e., the "killer" pulse), 4) damage to elevated highway systems, and 5) damage to welded moment steel frame buildings. Economic losses reached $ 40 billion with over $ 12 billion in insured losses; mortality 61, injured 15,000, and homeless over 50,000.

September 29, 1993 Khalari, India Earthquake [The Society for Earthquake and Civil Engineering Dynamics, 1993]

This M 6.3 earthquake is representative of the type of infrequent, but devastating moderate magnitude intraplate earthquakes that can occur in a low seismicity region on a shallow unknown fault system. This earthquake was a "surprise," not only because it occurred at great distance from the well known active Himalayan seismic belt in India's northern border region, but also because it happened at 3:46 a. m. on a Wednesday while people were sleeping in the supposed "security" of their unreinforced masonry homes typically having heavy stone roofs. This type of construction is well known for its vulnerability to earthquake ground shaking, but, because of the low seismicity, the potential risk was considered "acceptable." The end result is that they were not designed to withstand the level of strong ground shaking that occurred. Not a single house remained standing in Khilari. The estimated death toll reached at least 23.000.

July 12, 1993 Hokkaido-Nansei-Oki, Japan Earthquake

This M 7.8 earthquake, which occurred at 10:17 p. m. near Okushiri Island in the Japan Sea 30 km off the coast of southwest Hokkaido, is typical of subduction events along the recently recognized subduction plate boundary along the Japan Sea coast of northern Honshu and Hokkaido. Property loss was estimated at $ 600 million, and 197 were killed. Aonae, a small town of 500 on the southern end of Okushiri comprised mainly of 1-2 story buildings of wood post and beam construction, was heavily damaged from the ground shaking, tsunami flood waves, liquefaction, lateral spreads, loss of bearing strength, settlement, landslides, and a fire that started at 10:40 p. m. Because of the short source distance, tsunami warnings were ineffective for Aonae. Within 2-5 minutes after the earthquake, the largest tsunami flood waves ever to strike Japan began to arrive on the east coast of Okushiri while the ground was still shaking and at other locations within approximately 2 minutes after the shaking had stopped. Flood waves ranged from a vertical run up of 15 to 30 m in a 20 km portion of the southern portion of Okushiri Island and 10 m or less on the northern and western portions of the Island. The directivity of the fault rupture caused the duration of high frequency ground shaking, estimated to have reached 0.4 to 0.5 g at Aonae, to range from 1-2 minutes and to be longer east of the epicenter than in other directions. Because of the 30 km epicentral distance, engineered structures were not as vulnerable to ground shaking as they were to tsunami flood waves. The Japan Meteorological Agency issued a tsunami warning five minutes after the earthquake that a major (i.e., over 3 m) tsunami had been generated. Although the warning, which was issued through local television and radio stations, came too late to benefit the local populace, many of them were saved because they had run immediately for higher ground on the basis of past experience. The warnings were useful for other locations. The tsunami reached Russia in 20 minutes and South Korea in 90 minutes with wave run ups of 1-4 m in Russia and 1-2 m in South Korea

September 2, 1992 Offshore Nicaragua Earthquake

This M 7.0 earthquake, which occurred 120 km (70 miles) west-southwest of Managua at 6:45 p. m., is representative of what can be expected in the complex tectonic area where the Pacific, Caribbean, Cocos, and North American plates are converging. This event was not a subduction event, and apparently had a shallow focal depth. It produced a "surprise", in terms of its relatively small magnitude and the fact that it was not a subduction event, when it generated a tsunami which caused 8 m (30 foot) vertical flood wave run up that extended more than 1 km (0.5 mile) along a 330 km (200 miles) stretch of the Pacific coast. This stretch of the coast ranging from Porto de Corinto to the north to San Juan del Sur near the border with Coasta Rica, is comprised mainly of fishing villages and small resorts. The town of Masachapa, located 58 km (35 miles) southwest of Managua with a population of 25,600, was devastated by the tsunami flood waves which struck without any warning except the "noise of death" heard when the flood waves arrived at the coast. The known tolls were an estimated 500 deaths, many injuries, and 16,046 homeless.

October 11, 1992 Dashour, Egypt Earthquake

This M 5.9 earthquake, which occurred at 3:12 p. m., is representative of the type of infrequent, moderate-magnitude, but very damaging intraplate earthquakes that can occur in this part of the northeast corner of the African plate. Regional seismicity is controlled by the following plate boundaries: 1) to the north, the African and Eurasian plates which converge near Cyprus, 2) to the northeast, the Arabian and African plates, which are separated by the Levant transform, and 3) to the east and southeast, the Arabian and African plates, which are separated by the Red Sea spreading zone. The earthquake was located 25 km (15 miles) from Cairo, which has a population of 14 million and a very large inventory of non-engineered dwellings, buildings, and infrastructure. The earthquake demonstrated the well known vulnerability of unreinforced masonry buildings to ground shaking. Over 1,000 buildings, including a 14-story apartment building at Heliopolis which collapsed, many schools, and monuments were badly damaged. The economic toll reached $ 2 billion; over 700 were killed, and over 2,000 were injured. At the time of the earthquake, Egypt had not adopted a seismic building code, although one had been proposed in 1991 by the Egyptian Earthquake Engineering Society.

June 28-29, 1992 Landers-Big Bear, California Earthquakes

Located on different strike slip fault systems, these two earthquakes are representative of what should be expected along the Pacific and North American plate boundary in Southern California. Although rural earthquakes, they are important because of their contribution to the understanding of geologic processes in Southern California, the physics of surface fault rupture, transfer of stress to adjacent fault systems, and ground shaking; validation of damage from surface fault rupture; and calibration of the response of base-isolated buildings to strong ground shaking. The nature of their occurrence led to a new hypothesis that they may depict the San Andreas fault system attempting to cut a new path to get around the "big bend" in southern California. Landers (M 7.4), which occurred at 4:58 a. m., was the largest earthquake to occur in California since 1952. It generating right-lateral strike-slip surface fault rupture that extended northward for 85 km, starting on the Johnson Valley fault and continuing in a series of easterly steps across the Homestead Valley, Emerson, and Camp Rock faults. The Big Bear earthquake had a magnitude of 6.5 and occurred at 8.04 a. m.. More than 250 strong motion records were recorded from the two earthquakes with the Landers records characterized by long duration acceleration (i.e., "the killer pulse") and directivity effects, which were more pronounced in the direction of fault rupture. The records in the Law and Justice Center in San Bernardino County demonstrated the effectiveness of base isolation systems. In San Bernardino County, 77 homes were destroyed, 4.369 were damaged, and mobile homes were shown to be especially vulnerable to ground shaking. Ninety homes were damaged by surface fault rupture. Nearly all of these houses were built before the Alquist-Priolo Act was enacted into law in 1988. This Act required the California Division of Mines and Geology to construct special study zones to identify faults having the potential for surface rupture. All of the houses that were damaged would have been required to have a 50 foot setback from the fault zones that ruptured, of which 60% were recognized in field mapping. Only 1 death and 397 injuries were reported Losses were estimated at $ 100 million.

March 13, 1992 Erzincan, Turkey Earthquake

This M 7.1 earthquake, which occurred at 7:19 p. m., ruptured the same segment of the 1,000-km-long (600 miles) North Anatolian fault zone marking the boundary of the Eurasian and

Arabian plates that ruptured on December 26, 1939, in the M 8.0 Erzincan-Rafahiye earthquake. Surface fault rupture of 20 km (12 miles) was observed. The earthquake was like a "mini Mexico City" event, because it exposed the vulnerability of unreinforced masonry and non-ductile concrete buildings in a 125 km by 80 km (75 miles by 48 miles) alluvial valley which amplified ground motions in the 0.3-0.5 second range. Many of the 300 collapsed buildings, which included housing, schools, hospitals, and hotels, were 3-5 stories in height, underlain by soft alluvium , and susceptible to soil/structure resonance. The societal impacts were 653 dead, 3,850 injured, and about 50,000 homeless.

April 22, 1991 Coasta Rica Earthquake

This M 7.6 earthquake, which occurred at 3:55 p. m., is representative of the type of earthquakes that occur in conjunction with interactions of the Caribbean, North American, and Cocos plates. The earthquake demonstrated the vulnerability of unreinforced masonry buildings (homes, hotels) and bridges to ground shaking, highways to liquefaction, cracking, and landslides, underground utilities to ground failure, and ports, like Puerto Limon, to liquefaction and lateral spreads. Puerto Viejo and Cahota are examples of beach towns that were isolated when the only highway connecting them was made impassable because of landslides or damage to bridges. The death toll was 52.

July 16, 1990 Luzon, Philippines Earthquake

This M 7.7 earthquake, which occurred at 4:26 p. m., is representative of the type of earthquakes that are generated in this high seismicity region by two colliding plates: the Philippines Sea plate moving northwest and the Eurasian plate moving southeast. The Philippine Islands have a population of about 60 million with Luzon having about 4 million at risk to earthquakes which strike at frequent intervals. The earthquake was generated by slip on the 1,000-km-long, left-lateral, strike-slip Philippines fault which marks the interface of the colliding plates. Severe damage occurred in urban centers such as Dagupan, Gerona, Agoo, and Baguio, all of which are underlain by soft soils. In Dagupan, hotels collapsed from the ground shaking and the central business district was destroyed by extensive settlement of 1 m or more and liquefaction. The toll was at least 1,700 deaths, 3,500 injured, and 27,000 homeless.

June 21, 1990 Manjil, Iran Earthquake

This M 7.5 to 7.7 earthquake is representative of earthquakes occurring in the Zagros folded belt, the most active seismotectonic region of Iran. The earthquake demonstrated the vulnerability of unreinforced masonry houses and buildings to ground shaking and the destructiveness of landslides. Houses and infrastructure were shown to be especially vulnerable to rock falls triggered by the ground shaking. An estimated 50,000 were killed.

October 17, 1989 Loma Prieta, California Earthquake [State of California, 1990]

This M 7.1 earthquake, with an epicenter centered in a rural location 60 miles from San Francisco and Oakland, is representative of the type of earthquakes that occur along the right-lateral-strike-slip San Andreas fault zone in Northern California marking the active boundary of the North American and Pacific tectonic plates some distance from major urban centers. This earthquake occurred at 5:07 p. m. after many people had left work in San Francisco and Oakland to attend the World Series or to watch it at home on television. It destroyed unreinforced masonry buildings, damaged bridge systems, ruptured underground utilities, and left 63 dead, 11,000 injured, and 25,000 homeless in parts of San Francisco, Oakland, and other urban centers. Direct losses reached $8 billion. Many of the strong ground motion records acquired in the earthquake demonstrated the increased vulnerability of buildings and lifeline systems founded on soft Bay mud and land fill to enhanced ground shaking and permanent ground failure. It also demonstrated the fragility of unreinforced masonry buildings, elevated highway overpasses, airport runways, and underground pipelines to ground shaking, liquefaction, and lateral spreading, and reminded San Francisco of the continuing susceptibility of the Marina District and other areas to fire and lateral spreading.

December 7, 1988 Spitak, Armenia Earthquake [Earthquake Engineering Research Institute, 1989b]

This M 6.9 earthquake which occurred at 11:41 a. m. local time is representative of what can be expected from the ongoing collision of the Eurasian and Arabian tectonic plates. The earthquake exposed the well known lack of earthquake resiliency in old unreinforced masonry, but it presented a "surprise" when many new pre-cast reinforced concrete frame buildings collapsed. The ground motion levels in the epicentral region exceeded the design values due to soil amplification and proximity to the causative thrust fault. Schools and hospitals were also shown to be especially vulnerable. The death toll is believed to have reached at least 25,000 and the cost of reconstruction $16 billion.

September 19, 1985 Michiocan (Mexico) Earthquake [Earthquake (Engineering Research Institute, 1989a]

This M 8.1 earthquake, which occurred at 7:18 a. m., is representative of the great earthquakes that can be expected as a consequence of the ongoing subduction of the Cocos plate beneath the North American plate. The earthquake demonstrated the well known vulnerability to ground shaking of

5-20 story unreinforced masonry, non-ductile concrete, and reinforced concrete buildings (including hospitals, schools, and government buildings) located in the old lake bed zone of central Mexico City, the World's most populous urban center. Soil amplification, soil/structure resonance, and liquefaction contributed to the collapse of 5,728 buildings located in and adjacent to the old lake bed zone, a small fraction of the more than 1 million existing engineered buildings in Mexico City. As expected, the ground shaking recorded by accelerographs on firm soil in Mexico City generated by an earthquake located 400 km (250 miles) from the city in the subduction zone was low, in the order of 3% g. However, the soft soils underlying buildings constructed in the old lake bed amplified the firm soil ground motions for fundamental periods centered near 2 seconds by a factor of 5 or more to the order of 18 % g. The combination of soil amplification and soil/structure resonance caused the lateral load to exceed the capacity of many 5-20 story buildings located in the Old lake bed zone. .The vulnerability to fire was demonstrated when fires broke out in 350 places. An estimated 10,000 to 40,000 people were killed, 25,000 were injured, 200,000 were left homeless, and economic losses reached at least $5 billion. Design norms in effect for construction in and adjacent to the old lake bed zone at the time of the earthquake were changed after the disaster to increase the earthquake resilience of new construction.

November 15, 1980 Irpinia, Italy Earthquake

This M 6.9 earthquake, which occurred at 7:34 p. m. is representative of the normal faulting earthquakes that can be expected in Central Italy. The earthquake exposed the vulnerabilities of isolated mountain villages crowning the mountain tops, steep roads susceptible to blockage by landslides, narrow streets susceptible to closure by debris, and old unreinforced masonry buildings and nonductile concrete buildings susceptible to damage and collapse from ground shaking. The earthquake left economic losses of $ 3 billion, 5, 000 dead, and 9,000 injured.

October 10, 1980 El Asnam, Algeria Earthquake [Hays, W. W. and Rouhban, B. M., 1991]

This M 7.3 earthquake which occurred on a Friday_(i.e., the "weekend") is typical of the type of earthquakes that can be expected as a consequence of the ongoing collision of the Eurasian and African tectonic plates. The earthquake exposed the lack of earthquake resilience of existing as well as new buildings that were not designed to withstand the level of strong horizontal and vertical ground shaking that occurred in the epicentral region of the causative thrust fault. An estimated 9,612 people were killed or injured and the direct losses are believed to have reached $ 2 billion. Reconstruction was frozen until a seismic zonation study of ten urban centers could be completed and implemented through new building regulations and land use plans.

CONCLUSIONS

The postearthquake investigations have pointed out the mistakes that, either singly or collectively, have increased the vulnerability of physical elements in the community to the physical effects of the earthquake (i.e., to ground shaking, ground failure, surface fault rupture, tectonic deformation, aftershocks, tsunami flood waves, and fire following earthquake), and contributed to earthquake disasters. In many countries, these mistakes have been recognized and steps are being taken to adopt avoidance strategies or counter measures by integrated changes in planning, siting, design, construction, and land-use practices. The new avoidance strategies are:

1. Avoid sites having the potential for enhanced ground shaking from soil amplification and increased damage from the frequency-dependent resonance of soils and structures having similar fundamental periods of vibration (e. g., Mexico, Spitak, Loma Prieta, and Erzincan).
2. Avoid sites having soils that either can liquify or that are unstable and susceptible to large permanent displacements (e. g., Costa Rica, the Philippines, Loma Prieta, and Kobe).
3. Avoid sites having the potential for surface fault rupture (e. g., Landers)
4. Avoid sites on coasts susceptible to tsunami flood wave run up (e. g., Hokkaido-Nansei-Oki, Nicaragua).
5. Avoid sites where the severity, frequency composition, and duration of the lateral forces of ground shaking are enhanced by proximity to the causative fault, or by the effects of topography or source directivity (e. g., Kobe, Northridge, Loma Prieta, Spitak, Erzincan, El Asnam, and Irpinia).
6. Avoid sites where earthquake ground shaking effects are intensified by shallow brittle-ductile transition zones (e. g., Khalari and Kobe).
7. Avoid locations where structures are susceptible to pounding from adjacent structures (e. g., Mexico).

REFERENCES

Earthquake Engineering Research Institute [1995], The Hyogo-Ken Nanbu earthquake, Preliminary Reconnaissance Report 95-04, Oakland, California, 116 p.

Earthquake Engineering Research Institute, [1989a], The Mexico earthquake of september 19, 1985, Earthquake Spectra, Oakland, California, Vol. 4, 410 p.

Earthquake Engineering Research Institute [1989b], Armenian earthquake reconnaissance report, Earthquake Spectra, Special Report, Oakland, California, 175 p.

Earthquake Engineering Research Institute [1991],"*Earthquake response plan and field guide*", Publication 91-A, Oakland, California, 164 p.

Hays, W. W. and Rouhban, B. M. [1991], Technology transfer, Episodes, Vol. 14, pp. 66-72.

Society for Earthquake and Civil Engineering Dynamics [1993], The Khilari earthquake disaster, Newsletter, Manchester, England, Vol. 7, No. 4, pp. 1-2.

State of California [1990], Competing against time, Report of the Governors Board of Inquiry on the Loma Prieta Earthquake, North Highlands, California, 264 p.

State of California [1995], Northridge earthquake, turning loss to gain, Seismic Safety Commission Report 95-01 to the Governor, Sacramento, California, 160 p.

United States Geological Survey [1993], The national earthquake hazards reductionpProgram (NEHRP): postearthquake investigations, Open-File Report 93-528, Reston, Virginia, 14 p.